

# RELATIONS OF FIBER LENGTH TO WITHIN-TREE VARIATION OF ULTRASONIC WAVE VELOCITY IN FAST-GROWING TREES

*M. Hasegawa\**

Assistant Professor  
Department of Agro-Environmental Science  
Faculty of Agriculture  
Email: [kmgmtsm@agr.kyushu-u.ac.jp](mailto:kmgmtsm@agr.kyushu-u.ac.jp)

*M. Mori*

Graduate Student  
Graduate School of Bioresource and Bioenvironmental Sciences  
E-mail: [acoustoelasticity@gmail.com](mailto:acoustoelasticity@gmail.com)

*J. Matsumura*

Professor  
Department of Agro-Environmental Science  
Faculty of Agriculture  
Kyushu University  
6-10-1 Hakozaki, Higashi-ku Fukuoka, 812-8581, Japan  
Email: [matumura@agr.kyushu-u.ac.jp](mailto:matumura@agr.kyushu-u.ac.jp)

(Received December 2014)

**Abstract.** The within-tree variation of longitudinal wave velocities in *Acacia auriculiformis* (AA), *Eucalyptus dunnii* (ED), and *Melia azedarach* (MA) was experimentally investigated. The velocities in the longitudinal direction ( $V_L$ ) exhibited a minimum value near the pith. The minimum values in AA, ED, and MA were measured to be 4000, 4600 and 3600 m/s, respectively.  $V_L$  increased from the pith to the bark. On the other hand, the velocities in the radial and tangential directions exhibited constant values. The radial variation patterns of the  $V_L$  coincided with those of fiber length (FL).  $V_L$  exhibited a strong correlation with the FL at a 1% significant level. These findings revealed that wood properties such as FL greatly influence the velocity in the longitudinal direction.

**Keywords:** Fast-growing tree, ultrasonic wave, velocity, hardwood, fiber length.

## INTRODUCTION

Fast-growing trees could contribute to lowering the impact of global warming because of their high carbon-stocking capacity. Generally, fast-growing trees are used as pulping materials due to their high productivity. Fast-growing trees grow rapidly for a short period and have a large trunk diameter. Using fast-growing trees as a building material (eg as posts and beams in timber construction) increases their value. Experimental research has described physical and mechanical properties of some fast-growing trees such as the *Eucalyptus* species (Yang and Waugh

1996a,b; Llic 2001; Yang and Evans 2003; Thomas et al 2009), the *Acacia* species (Shukla et al 1990, 2007; Hai et al 2010), and *Melia azedarach* (MA) (Shukla et al 1990; Venson et al 2008). Venson et al (2008) experimented with the physical, mechanical, and biological properties of MA in Mexico. They demonstrated that MA could be used as structural lumber if the appropriate genotypes and clones were selected. For Japanese fast-growing trees, Matsumura et al (2007, 2006) reported compression strength variations in the stems of MA and modulus of elasticity and modulus of rupture variations in the stems of *Choerospondias axillaris*. Hasegawa et al (2010) demonstrated the potential of applying the acoustoelastic

---

\* Corresponding author

effects experimentally to determine the stress condition of MA.

An ultrasonic technique has been researched to be applied to the quality control of timber materials (Sandoz 1989) and to the maintenance of posts and beams in wooden construction (Hasegawa et al 2012, 2010). The ultrasonic velocity is an important parameter in the nondestructive testing of wood. The ultrasonic wave velocity in trunk wood is not uniformly distributed because the trunk is an anisotropic material. Such inhomogeneous distributions make it difficult to apply ultrasonic techniques to a wooden construction as a nondestructive testing method; therefore, we must know the distributions of velocities and clarify the mechanism of distributions. For softwood, the ultrasonic wave velocities in the longitudinal direction ( $V_L$ ) vary from the pith to the bark. Bucur (2006) reported this behavior for Douglas fir (*Pseudotsuga menziesii*). Hasegawa et al (2011) also reported this behavior for Japanese cedar (*Cryptomeria japonica*) and Japanese cypress (*Chamaecyparis obtusa*). They demonstrated that the tracheid structures (ie tracheid length and microfibril angle) greatly influence  $V_L$ . However, until now, there were few reports for within-tree variation of  $V_L$  for fast-growing trees.

The objective of this study is to elucidate the effect of wood properties on within-tree variation in the ultrasonic velocity in fast-growing trees. In this experiment, *Acacia* species, *Eucalyptus* species, and MA were used as the test specimens. Velocities propagated through the longitudinal, radial, and tangential directions were measured with the sing-around method (Hasegawa and Sasaki 2004). In addition, the radial variation in velocities and fiber length (FL) were measured. From these radial variations and the correlations among them, the mechanism of velocity distribution in fast-growing trees was investigated.

MATERIALS AND METHODS

Materials

Two 10-yr-old *Acacia auriculiformis* (AA) in Indonesia, two 8-yr-old *Eucalyptus dunnii* (ED)

Table 1. Air-dried density and MC of test specimens.

Species	Air-dried density (kg/m <sup>3</sup> )	MC (%)
<i>Acacia auriculiformis</i>	679	9.43
<i>Eucalyptus dunnii</i>	686	9.51
<i>Melia azedarach</i>	563	9.87

in Australia, and 22-yr-old MA in Japan were used as the test materials. Strips with 3 cm thickness were cut from wood disks in air-dried conditions to measure the velocities of ultrasonic waves in the longitudinal and tangential directions. Thereafter, the strips were sliced into 1 cm pieces to measure velocities in the radial direction. The air-dried density and MC of test specimens are shown in Table 1.

Ultrasonic Measurement

For measuring velocities in the longitudinal and tangential directions, an ultrasonic sensor was slid from the pith toward the outside in 1 cm steps, and the ultrasonic wave velocity was measured at every position of the sensor. The velocity in the radial direction was measured at 1 cm intervals on each sliced piece, starting from the pith and sliding the sensor toward the outside.

The ultrasonic velocity was measured with the sing-around, using a model UVM-2 unit (Ultrasonic engineering, Tokyo, Japan). Piezoelectric transducers with a natural frequency of 0.5 MHz and a diameter of 2.5 cm (models CR-0016-S for longitudinal waves by Staveley Instruments, Washington, USA) were used to detect the ultrasonic waves. Silicone grease (SH111 by Dow Corning Toray, Tokyo, Japan) was used as the coupling medium to improve the bonding between the transducers and the wood specimen, and a rubber band held the transducers against the specimen as shown in Fig 1.

Fiber Length

After ultrasonic measurement, a small piece was removed from the outermost side of each sliced piece. The small piece was macerated by treating it with of a 1:1 mixture solution of glacial

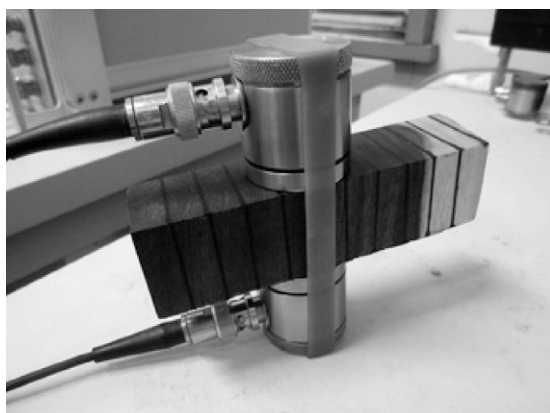


Figure 1. Setup for ultrasonic velocity measurement.

acetic acid and 30% hydrogen peroxide for 48 h at 80°C. After staining the macerated fibers with safranin, they were observed at 50-times magnification with a profile projector (model V-12 by Nikon Instruments, Tokyo, Japan), and their FLs were measured. At each point, 30 FLs were averaged.

## RESULTS AND DISCUSSION

### Radial Variation in Longitudinal Wave Velocities within the Wood Trunk

Figure 2 shows the radial variation of velocity in three orthotropic directions for the three wood species. The longitudinal wave velocities ( $V_L$ ) exhibited a minimum value near the pith. The minimum longitudinal wave velocity for AA, ED, and MA were 4000, 4600, and 3600 m/s, respectively.  $V_L$  kept increasing toward the outside and attained values of 5000, 5400, and 4600 m/s at the furthest points of measurement, respectively.  $V_L$  in this study varied from pith toward the outside similar to the behavior of  $V_L$  in softwood (Bucur 2006; Hasegawa et al 2011). The velocities in the radial and tangential direction ( $V_R$ ,  $V_T$ ) remained constant as shown in Fig 2. The three fast-growing trees used in this study are hardwoods. Until now, there have been no reports of radial variations of  $V_L$ ,  $V_R$ , and  $V_T$  in hardwood. For the first time, we have experimentally confirmed the radial variations of velocity. As mentioned in the introduction,  $V_L$

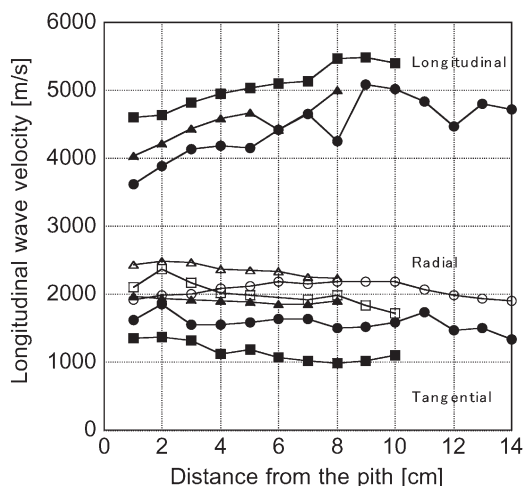


Figure 2. Radial variations in the longitudinal wave velocities in three orthotropic directions, triangle: AA, square: ED, circle: MA.

for softwood is influenced by the tracheid structures. For hardwood, the wood fibers are oriented parallel to the axial direction. In the next section, we focus on FL to examine the effect of wood properties on  $V_L$ .

The average velocities along all three directions are summarized in Table 2. As there have been no data for  $V_L$ ,  $V_R$ , and  $V_T$  in AA, ED, and MM until now, it is difficult to compare the values of  $V_L$  in this study with those of previous works; however, we can examine the values of velocities in similar wood species. As shown in Table 3, the results for AA and ED in this study are consistent with these previous studies.  $V_L$  exhibited the largest wave velocities of the three directions. The values of longitudinal velocities in wood are known to increase in the following order:  $V_L$ ,  $V_R$ ,  $V_T$ . For hardwood, wood fibers and vessels are oriented longitudinally. As a result of this structural anisotropy,

Table 2. Ultrasonic wave velocities in the three orthotropic directions.

Species	$V_L$ (m/s)	$V_R$ (m/s)	$V_T$ (m/s)
<i>Acacia auriculiformis</i>	4500 ± 296	2368 ± 94	1902 ± 39
<i>Eucalyptus dunnii</i>	5060 ± 322	2012 ± 188	1151 ± 143
<i>Melia azedarch</i>	4500 ± 410	2035 ± 121	1566 ± 117

Table 3. Velocities in the longitudinal direction in this study and previous studies.

Species	$V_L$ (m/s)	Air-dried density ( $\text{kg/m}^3$ )
<i>Acacia auriculiformis</i>	4500	679
<i>Eucalyptus dunnii</i>	5060	686
<i>Acacia mangium</i> (Sharma and Shukla 2012)	4100	470
<i>Acacia mangium</i> (Hamdan et al 2011)	5144	520
<i>Eucalyptus grandis</i> (Fabiana and Almir 2006)	5100	660

Table 4. Ratio of longitudinal wave velocity in three directions.

Species	$V_L/V_R$	$V_L/V_T$	$V_R/V_T$
<i>Acacia auriculiformis</i>	1.9	2.4	1.2
<i>Eucalyptus dunnii</i>	2.5	4.4	1.7
<i>Melia azedarach</i>	2.2	2.9	1.3

the velocity is fastest in the longitudinal direction. The ratios between  $V_L$ ,  $V_R$ , and  $V_T$  were obtained from the data in Table 2. These ratios are shown in Table 4. The ratios obtained in this study are consistent with the findings of Bucur (2006), who reported that  $V_L/V_R$  and  $V_L/V_T$  ratios for hardwood ranged from 1.7 to 2.8 and 2.3 to 4.2, respectively.

Relationships between Longitudinal Wave Velocities and Fiber Length

Figure 3 shows the radial variations in  $V_L$  and FL for AA, ED, and MA. The variations in  $V_L$  from Fig 2 are included in Fig 3 for comparison. FL values were at a minimum near the pith, and their values were 0.7 mm for AA, 0.7 mm for ED and MA. These FL gradually increased to 1.0 mm for AA, 0.9 mm for ED and MA toward the outside. Chowdhury et al (2009) reported that the FL in 11-yr-old AA in Bangladesh ranged from 0.89 to 1.06 mm. Matsumura et al (2006) reported that the averaged FL over the 10th ring in 17-yr-old MA in Japan ranged from 0.86 to 1.02 mm. FL measurements obtained in this study were consistent with the FL measurements from those studies. As shown in Fig 3, the variation patterns of the FL in the radial direction coincided with those of  $V_L$ .

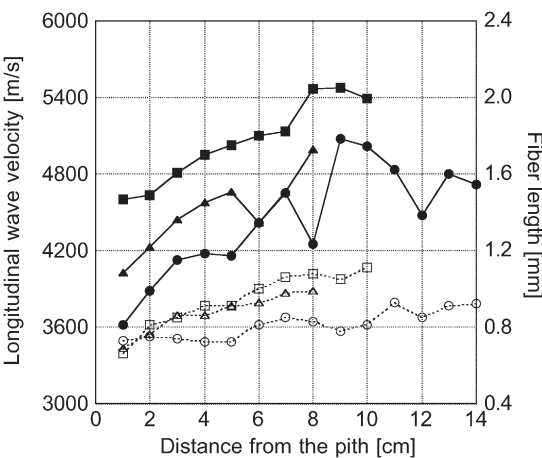


Figure 3. Radial variations in longitudinal wave velocities and FL, solid lines: longitudinal wave velocity, dotted lines: FL, triangle: AA, square: ED, circle: MA.

Figure 4 shows the relationships between  $V_L$  and FL.  $V_L$  was related positively with FL at 1% significant level. Correlation coefficients between  $V_L$  and FL were 0.90 for AA, 0.92 for ED, and 0.68 for MA. Polge (1984) reported a strong correlation ( $r = 0.90$ ) between the FL and  $V_L$  for a cherry tree. Baar et al (2013) reported that  $V_L$  in the tropical hardwoods (*Afzelia bipindensis*, *Intsia bijuga*, and *Astronium graveolens*) was strongly related to FL. Their correlation coefficients were

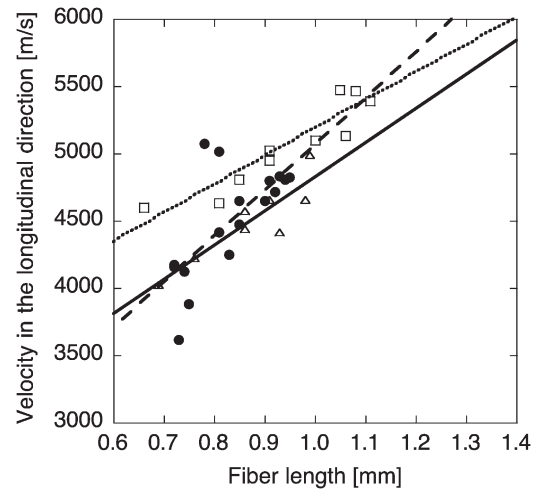


Figure 4. Relationships between longitudinal wave velocities and FL, open triangle: AA, open square: ED, filled circle: MA, solid line: AA, dotted line: ED, broken line: MA.

0.92, 0.82, and 0.81, respectively. In addition, Bucur (2006) made the point that an ultrasonic wave dissipates the acoustical energy when it takes place at the end of fiber. The FL contributes, in part, to the radial variations in  $V_L$ . On the other hand, Baar et al (2013) demonstrated that the ray ratio, which is the ratio of ray height to ray width, was strongly related to  $V_L$ , suggesting the ray dimensions is one of the most important anatomical characteristics determining  $V_L$ . Further experiments will be needed to determine the relationships between  $V_L$  and ray dimensions in fast-growing trees. However, until our study, there has been no measurement of the relationship between  $V_L$  and FL. On the other hand,  $V_R$  and  $V_T$  remained constant as shown in Fig 2. Further research is required to determine why  $V_R$  and  $V_T$  show no variation from the pith to the bark. The structure of hardwood is more complex than that of softwood. Hardwood mainly consists of wood fiber, vessel element, and parenchyma. It would, therefore, be interesting to investigate the relationship between  $V_R$  and  $V_T$  and cell dimensions for hardwoods other than those examined in this study.

### CONCLUSIONS

The within-tree variation in longitudinal wave velocities in AA, ED, and MA was experimentally investigated. The velocities in the longitudinal direction ( $V_L$ ) changed from the pith toward the bark, while those in the radial and tangential directions exhibited constant values. As above, the radial variations of ultrasonic wave velocity in fast-growing trees were measured for the first time.  $V_L$  exhibited a strong correlation with the FL at a 1% significance level. These findings revealed that FL greatly influences the velocities in the longitudinal direction; however, FL is not the sole determinant of the velocities. Microfibril angle, density, and MC are also important factors. Therefore, a multivariate statistical analysis is required to determine which wood properties have a significant impact on  $V_L$ . We will clarify the mechanism of radial variations in ultrasonic wave velocity in fast-growing trees.

In addition, it is essential to elucidate the mechanical properties and growth characteristics to produce the sustainable and stable fast-growing trees. The radial variation in ultrasonic velocity is a useful indicator for elucidation of mechanical properties within the wood trunk. We will clarify the relations between ultrasonic velocity, mechanical properties, and growth characteristics in the future.

### ACKNOWLEDGMENTS

We sincerely thank Professor Yasutoshi Sasaki (Graduate School of Bioagricultural Science, Nagoya University) for providing the instrument to measure the ultrasonic wave velocity. We also thank Professor Susumu Shiraishi (Faculty of Agriculture, Kyushu University) for providing wood samples of *Acacia auriculiformis* and *Eucalyptus dunnii*. The publication was supported in part by the Research Grant for Young Investigators of Faculty of Agriculture, Kyushu University.

### REFERENCES

- Baar J, Tippner J, Gryc V (2013) The relation of fibre length and ray dimensions to sound propagation velocity in wood of selected tropical hardwoods. *IAWA J* 34(1): 49-60.
- Bucur V (2006) *Acoustics of Wood*, 2nd ed. Springer-Verlag, Berlin. pp. 142-147.
- Fabiana GRO, Almir S (2006) Relationship between density and ultrasonic velocity in Brazilian tropical woods. *Biores Technol* 97(18):2443-2446.
- Chowdhury MQ, Ishiguri F, Iizuka K, Hirakawa T, Matsumoto K, Takashima Y, Yokota S, Yoshizawa N (2009) Wood property variation in *Acacia auriculiformis* growing in Bangladesh. *Wood Fiber Sci* 41(4):359-365.
- Hai PH, Hannrup B, Harwood C, Jansson G, van Ban D (2010) Wood stiffness and strength as selection traits for sawn timber in *Acacia auriculiformis*. *Can J For Res* 40(2):322-329.
- Hamdan S, Liew YL, Hasan M, Talib ZA (2011) Studies of monomer impregnation and polymerized *in situ* in wood using dynamic mechanical thermal analyzer. *Mater Sci Technol* 27(1):40-43.
- Hasegawa M, Sasaki Y (2004) Acoustoelastic birefringence effect in wood I: Effect of applied stresses on the velocities of ultrasonic shear waves propagating transversely to the stress direction. *J Wood Sci* 50(1):47-52.



- Hasegawa M, Matsumura J, Kusano R, Tsushima S, Sasaki Y, Oda K (2010) Acoustoelastic effect in *Melia azedarach* for nondestructive stress measurement. *Construct Build Mater* 24(9):1713-1717.
- Hasegawa M, Takata M, Matsumura J, Oda K (2011) Effect of wood properties on within-tree variation in ultrasonic wave velocity in softwood. *Ultrasonics* 51(3):296-302.
- Hasegawa M, Yano Y, Matsumura J, Oda K (2012) Prospects for within-tree variation of the acoustoelastic behaviors in Japanese cedar. *NDT Int* 49(7):57-63.
- Llic J (2001) Relationship among the dynamic and static elastic properties of air-dry *Eucalyptus delegatensis* R. Baker. *Holz Roh Werkst* 59(3):169-175.
- Matsumura J, Inoue M, Yokoo K, Oda K (2006) Cultivation and utilization of Japanese fast growing trees with high capability for carbon stock I. Potential of *Melia azedarach*. *Mokuzai Gakkaishi* 52(2):77-82 [In Japanese with summary in English].
- Matsumura J, Tanoue M, Ogata R, Gyokusen K, Muta S, Kamiwaki K, Hasegawa M, Oda K (2007) Cultivation and utilization of Japanese fast growing trees with high capability for carbon Stock II. Potential of *Choerospondias axillaris*. *Mokuzai Gakkaishi* 53(3):127-133 [In Japanese with summary in English].
- Polge H (1984) Essai de caractérisation de la veine verte du merisier. *Ann Sci For* 41:45-58 [In French with summary in English].
- Sandoz JL (1989) Grading of construction timber by ultrasound. *Wood Sci Technol* 23:95-108.
- Shukla NK, Mohan L, Singh RS, Khanduri AK (1990) Physical and mechanical properties of *Acacia auriculiformis*, *Fernandoa adenophylla*, and *Melia azedarach*. *J Timb Dev Assoc* 36(2):31-45.
- Shukla SR, Rao RV, Sharma SK, Kumar P, Sudheendra R, Shashikala S (2007) Physical and mechanical properties of plantation-grown *Acacia auriculiformis* of three different ages. *Aust For* 70(2):86-92.
- Sharma SK, Shukla SR (2012) Properties evaluation and defects detection in timbers by ultrasonic non-destructive technique. *J Ind Acad Wood Sci* 9(1):66-71.
- Thomas D, Henson M, Joe B, Boyton S, Dickson R (2009) Review of growth and wood quality of plantation-grown *Eucalyptus dunnii* Maiden. *Aust For* 72(1):3-11.
- Venson I, Guzmán JAS, Talavera FJF, Richter HG (2008) Biological, physical and mechanical wood properties of paraíso (*Melia azedarach*) from a roadside planting at Huaxtla, Jalisco, Mexico. *J Trop For Sci* 20(1):38-47.
- Yang JL, Evans R (2003) Prediction of MOE of eucalypt wood from microfibril angle and density. *Holz Roh Werkst* 61(6):449-452.
- Yang JL, Waugh G (1996a) Potential of plantation-grown eucalypts for structural sawn products I. *Eucalyptus globulus* Labil. ssp. *globulus*. *Aust For* 59(2):90-98.
- Yang JL, Waugh G (1996b) Potential of plantation-grown eucalypts for structural sawn products II. *Eucalyptus nitens* (Dean & Maiden) Maiden and *E. regnans* F. Muell. *Aust For* 59(2):99-107.